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Thermoelectric energy harvester fabricated by Stepper

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ABSTRACT

In this paper, a micromachined thermoelectric energy harvester with 6 μm high thermocouples is fabricated by Stepper technology. Micromachined thermocouples are considered a cost-effective breakthrough solution for energy harvesters working at low thermal gradients and weak heat flows, typical for e.g. human body as well as machine-related waste heat. The thermoelectric generators will be used for autonomous wireless sensor nodes in a body area Network.

1. Introduction

Temperature differences in/on artificial objects (machinery, buildings, transport, pipelines) and on the skin of animals and man can be used to power autonomous devices. For example, the first wearable wireless sensors and medical devices (Electroencephalograph (EEG) system, an Electrocardiography System in a Shirt) fully powered by thermoelectric generators (TEG) on man have been recently demonstrated [1–3] (Fig. 1).

Currently, commercial thermal energy harvesters are assembled manually by using off-the-shelf bulk materials and are very expensive. However, the cost of energy harvesters is an important factor for their acceptance by industry and for moving them into mass production. Reduction of the cost can be achieved using micromachining technologies, fabricating many devices in one run. It is the subject of this paper to discuss the development of micromachined thermoelectric harvesters.

The design of the thermopile over a large topography is shown in Fig. 2a. To reach the target performance in micromachined thermopiles, the height of the thermocouples has to be as large as possible. For example, a height of about 10–15 μm allows reaching the optimal performance: A voltage of around 5 V and a power of 3 $\mu W/cm^2$ [4]. However, already 6 μm (which is more feasible), could offer a useful performance characteristic at a contact resistance between semiconducting legs and interconnecting metal of the order of 100 $\Omega\,\mu m^2$. In a low heat flow regime, i.e. in energy harvesters, the density of thermocouples per unit surface must be as large as possible to get a useful voltage output (~1–2 V), which means the lateral size of thermocouples must be a few micrometers. Therefore, the thermopile performance is limited by photolithography. In order to reach good performance characteristics a gap between the neighbor thermocouple legs must be about 2 μm or even smaller on topography with a height of 6–10 μm.

In [4], the benefit is discussed of using Stepper technology. The Depth of Focus (DOF) of Stepper is simulated and from the simulation results, one observation is that at a feature size of 3 μm the DOF is as high as about 10 μm.

2. Fabrication

2.1. Thermocouples fabrication

A thermoelectric energy harvester consists of many thermocouples in series which are mounted between cold and hot plate. In our design, thermocouples are made on silicon substrate, which performs as hot plate. Another silicon substrate is bonded on top of devices and functions as cold plate (see Fig. 2b).

In the process, a 6 μm thick sacrificial layer is required, on which the thermocouples are fabricated. We use silicon oxide (PECVD), because it is removable and can tolerate high temperature through all process steps. SiGe is used as thermoelectric material because it is the best material readily available to be deposited

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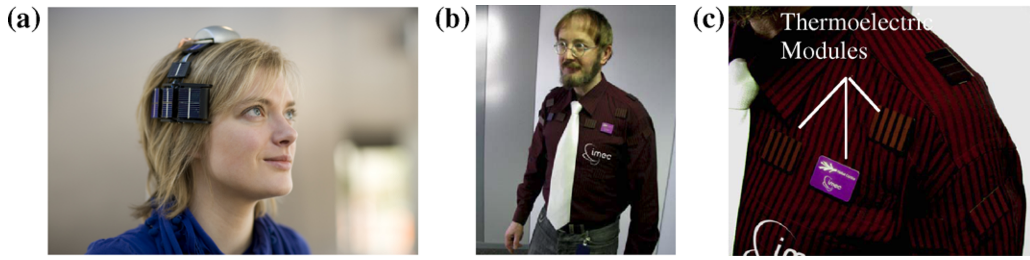

Fig. 1. (a) Wearable wireless EEG system with thermoelectric-photovoltaic power supply [2], (b) and (c) Electrocardiography shirt and some of its thermoelectric modules. The TEG modules are chameleon-like painted for invisibility. One of the modules has a different color to give an idea about its size [3].

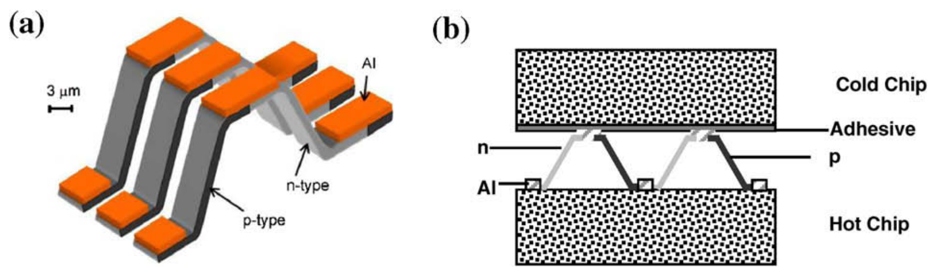

Fig. 2. (a) Design of the large topography thermocouple (three thermocouples are shown). (b) Schematic of thermoelectric energy harvester (Cross Section View).

over topography. After deposition of the 6 μm thick silicon oxide and subsequent lithography, the silicon oxide is etched into bumps (see Fig. 3a). Since it is very difficult to pattern thermocouples over a vertical wall, a certain angle is needed for the slope of the oxide bumps (in our case it is 30°). A layer of 150 nm thick silicon nitride is deposited, acting as an electrical insulator between device and substrate (Fig. 3b). Then intrinsic SiGe is deposited (c), implanted to become n- and p-type alternatively (d), and then patterned and annealed (e). The width of thermocouples that we fabricated is between 3 μm and 10 μm with a spacing of 2 μm between each other. Note that the width variation of thermocouples has to be no more than 10% over the whole 6 μm high bump, as well as on top and the bottom [4]. A special mask design and process is used, which is discussed in [5]. Next, Al is used as metal contact which is deposited and patterned. Finally, the thermocouples are released by PAD etch [5]; see Fig. 4a.

2.2. Bonding technique

Next step is the bonding of the top chip (cooling plate of the harvester) to the substrate containing the thermocouples. This bond needs to supply a good thermal connect to the cooling plate, while at the same time electrical shorts between the legs need to be avoided. There are two possible ways for this kind of bonding: one is metal-to-metal bonding and the other is adhesive bonding.

For metal-to-metal bonding, a metal layer is deposited and patterned on the wafer. Because the distance between each thermocouple is very small (2 μm), the alignment between top substrate and bottom substrate (less than 2 μm), is extremely critical for current bonding alignment, otherwise a short between legs will occur. Moreover, metal-to-metal bonding requires applying high pressure during bonding which can easily break thermocouples during bonding.

Normally, glue or epoxy is used for adhesive bonding. There are two important parameters related to our design. First, the thickness of the film has to be as small as possible (around 1 μm), in order to prevent that during bonding the gaps in between the thermopiles will be (partially) filled by the adhesive, thereby reducing the effective height of the thermopiles. Second, a high thermal conductance is preferable, which implies a thin layer of adhesive. Since the thermal conductivity of adhesives is not as good as metal, a thickness larger than 1 μm would result in a large interfacial thermal resistance. Typically, adhesives have a thermal conductivity between 0.3 and 3 W/mK, which is much smaller than the thermal conductivity of Si, which is around 150 W/mK. In principle the thermal conductivity of adhesives can be increased by

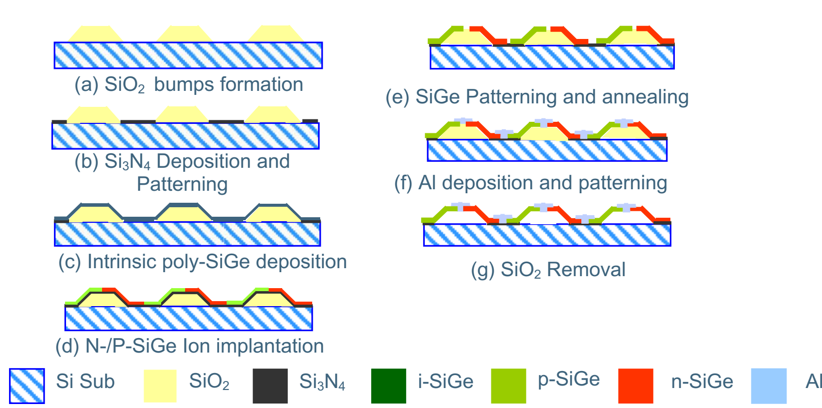

Fig. 3. Process flow of thermocouple fabrications.

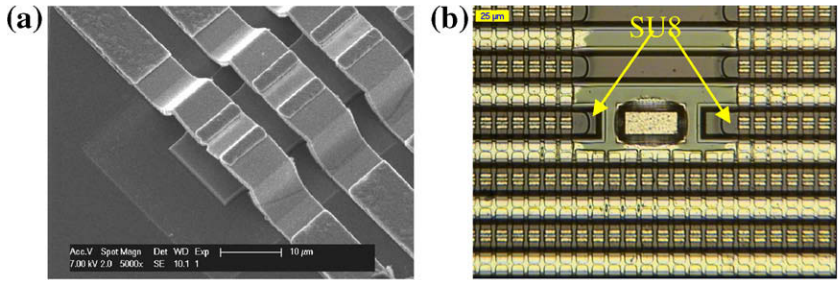

Fig. 4. (a) SEM Photo of released thermocouples. (b) SEM photo of Bonding Cross Section.

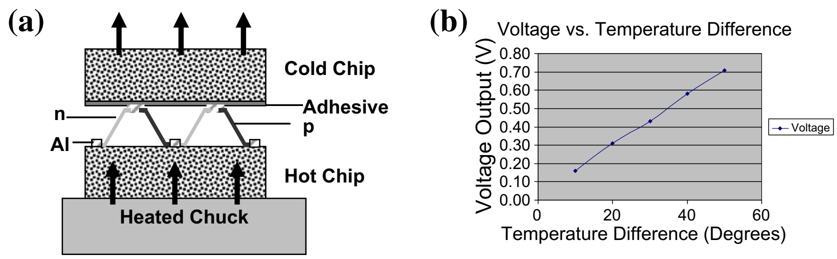

Fig. 5. (a) Schematic of measurement. (b) Voltage output of a functional device.

adding thermal conductive fillers, but since the size of these fillers is ⩾2 μm, we would again be faced with the problem of adhesive filling the gaps between the thermopiles.

We therefore ended up using SU8-2002, which is a good material for bonding with a layer less than 1 μm and a reasonable thermal conductivity of 0.3 W/mK. SU8–2002 is frequently used for bonding. It starts to reflow at a temperature above 80 °C and cross-links when temperature reaches 150 °C. We have optimized the bonding parameters. To have a visual check, we have bonded a transparent Pyrex wafer on top, which is shown in Fig. 4b. One can clearly see the nice bonding between the thermopiles and the Pyrex wafer.

3. Measurement

After the successful bonding, devices are measured on a thermal chuck (see Fig. 5). In this first experiment, different voltage outputs, from 0.15 to 0.70 V, are measured as a function of temperature difference between the chuck and the ambient temperature of 22 °C (see Fig. 5b). We assume the temperature on the cold plate is same as the ambient temperature. Note that the actual temperature difference over the thermopiles is smaller because there are also thermal gradients present across the hot and the cold chip. The most important result of this measurement is the fact that indeed all the 1300 thermocouples (10 μm wide and all connected in series) are intact and the device is functional. Further measurements are ongoing to determine the exact temperature difference and also the power output, which will be presented later [6].

4. Conclusion

In this paper, a functional SiGe thermoelectric energy harvester is fabricated and measured. A voltage can be generated which is a function of temperature, showing the functionality of the device. More devices will be characterized and the power output will be determined [6]. In future, we will look for other materials which have a higher overall thermal efficiency than SiGe [7] (e.g. BiTe, superlattices).

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